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INTRODUCTION

The proposed site for the Synthetic Aperture Sonar (SAS) component of the Coastal Mixing and Optics Experiment is 40.5°N and 70.5°W. A survey of historical CTD casts has been done to determine the general acoustic propagation characteristics for this area and assess how the propagation conditions vary with bottom depth near the SAS site. The goal of SAS is to identify ocean processes that produce acoustic fluctuations in the water volume. This implies knowing the depths that the rays have sampled. We also must be able to separate ray arrivals when using pulses with moderate bandwidths.

This report describes the survey and features of the propagation over the area of the SAS site. Casts made in water depths of 60–80 m are examined in further detail. In all cases, raytracing is used to characterize the propagation. A numerical differential-equation solver that obtains the ray variables appropriate for the Helmholtz equation is used throughout. We conclude that propagation conditions are quite favorable for the experiment involving propagation between two towers in water depths of 60–80 m. Both shallower and deeper sites are less favorable and pose problems for the success of SAS. In drawing these conclusions, we have not considered the portion of the SAS experiment that involves propagation between a tower and a towed receiver.

THE SURVEY

For our survey, we used NODC's 1994 *World Ocean Atlas* recently released on CD-ROM, which contains vertical profiles made in this century up to 1992. Out of nearly 80 CTD casts taken in July and August from the rectangle 40–41.5°N and 70–72°W, about 30 were at locations having bottom depths from 40–100 m. These casts are from the years 1974, 1976, 1979, 1982, and 1987.

Figure 1 shows the area south of Woods Hole where the SAS experiment will occur. The 30 CTD locations are depicted by boxes. Casts in which temperature decreases near the bottom are shown by open boxes. Casts with a duct at mid-depth or increasing temperature at depths below 50 m (and hence upward-bending rays near the bottom) are shown by crossed boxes. The latter casts are influenced by waters found off the shelf and tend to be in deeper water south of 40.5°N.

Note that the proposed site is bracketed by shipping lanes. The western portions of these lanes are depicted by dashed lines in the figure. Although the site looks like it is in the median of a freeway, there are, in fact, 6 nautical miles between the lanes. We have also been told that fishing gear may pose a greater problem than cargo traffic.

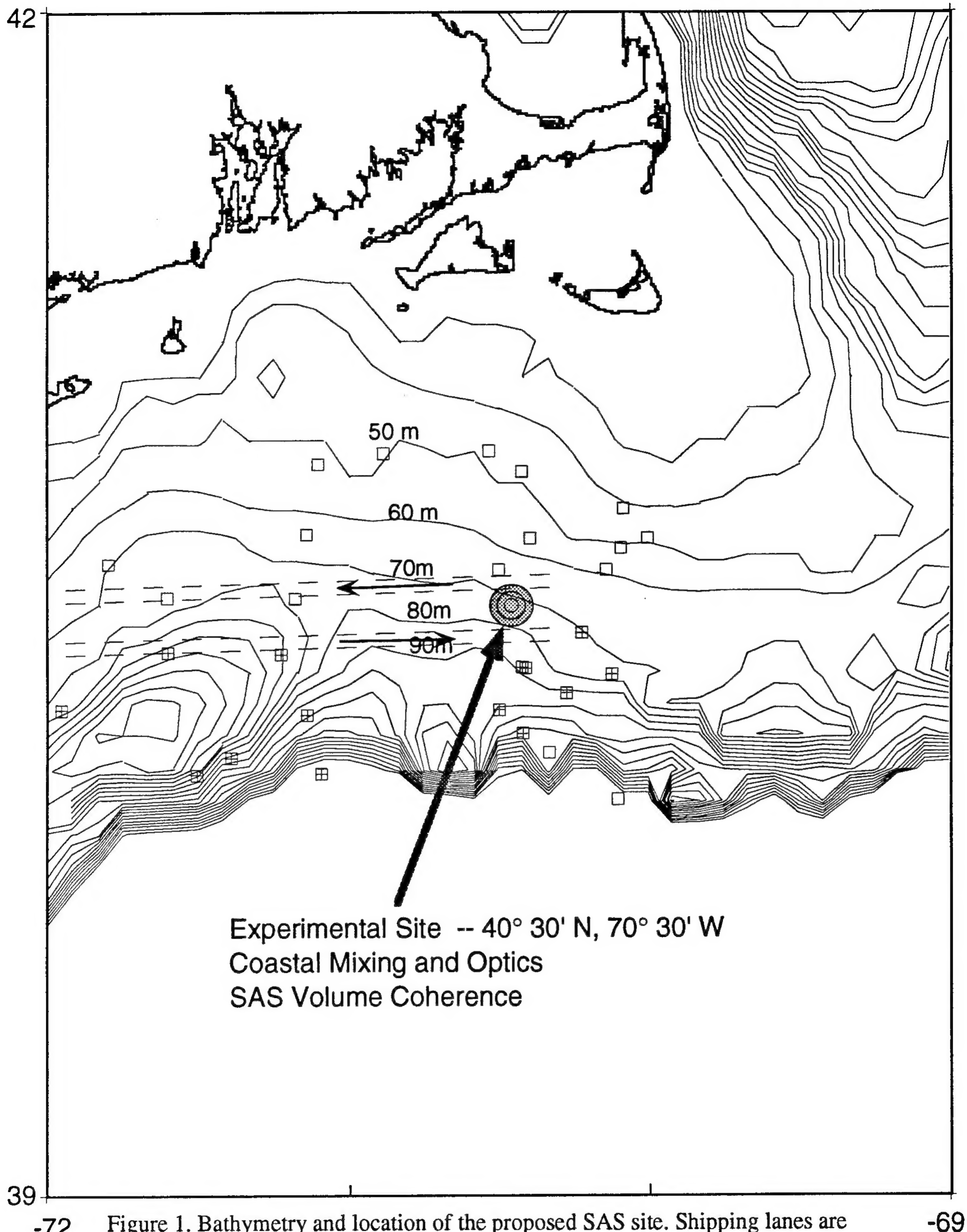


Figure 1. Bathymetry and location of the proposed SAS site. Shipping lanes are shown by the dashed lines; arrows show the transit direction. Open boxes are locations of CTD casts where sound speed decreases over the entire depth range of the profile. Crossed boxes are locations of CTD casts that have either an increasing sound speed near the bottom or a duct at some depth.

GENERAL PROPAGATION CHARACTERISTICS

Consider the situation where there is a movable transmitter 10 m above the bottom and a receiving array at the same depth and at most 1000 m away in range. Figure 2 displays raytraces for three bottom depths: shallow (< 60 m), intermediate (68 m), and deep(>80 m). Note that the figure shows only volume rays; we will say a bit about rays that interact with the surface and the bottom later.

In these three examples, there are common features that we can identify. Near the transmitter, there is a region where the rays are nearly horizontal. A receiver placed here would receive a single arrival. As range increases, at least two caustics occur. These caustics are associated with rays that leave the transmitter at higher angles and turn in the thermocline. A receiver placed at a range between the two caustics would receive three rays.

At ranges beyond the second caustic, only rays turning in the shallower thermocline or near the mixed layer would be received. These rays would have a lower intensity than those leaving the transmitter at a smaller angle. This is the situation for a profile where the sound speed gradient decreases at depth (and hence rays that leave the transmitter at a downward angle refract downward). For a profile with increasing sound speed at depth, near-horizontal rays would reach a receiver at longer ranges.

The shallow-depth case is shown at the top of Figure 2. Because the transmitter is relatively close to the thermocline, the first caustic is relatively close to the transmitter. The propagation region of rays leaving the transmitter at near-horizontal angles is very short. At long range, weaker rays arrive, and there is a large area having few arrivals (a shadow zone) above the second caustic.

The middle panel in Figure 2 shows the intermediate-depth case. All regions are expanded in range relative to the shallow-depth case. The caustic curve intersects the bottom at about 500 m in range, and the area of three arrivals extends beyond 1000 m.

For the deeper case (bottom of Figure 2), the area with three ray arrivals is now past 1000-m range. Only near-horizontal arrivals reach a receiver at a range less than 1000 m. This is less desirable than the previous case because we want to sample rays that turn in the depth interval containing the high sound-speed gradient. This interval is associated with high buoyancy frequencies, and rays that turn at these depths will have much larger fluctuations than the nearly horizontal rays at short range.

In fact, both the near-horizontal and the steeper rays are of interest. Even with the known variability in space and time in the coastal environment, the historical data suggest that we would increase our chances of sampling both types of rays by placing our equipment where bottom depths are 60–80 m. The proposed site with a bottom depth near 70 m meets this criterion.

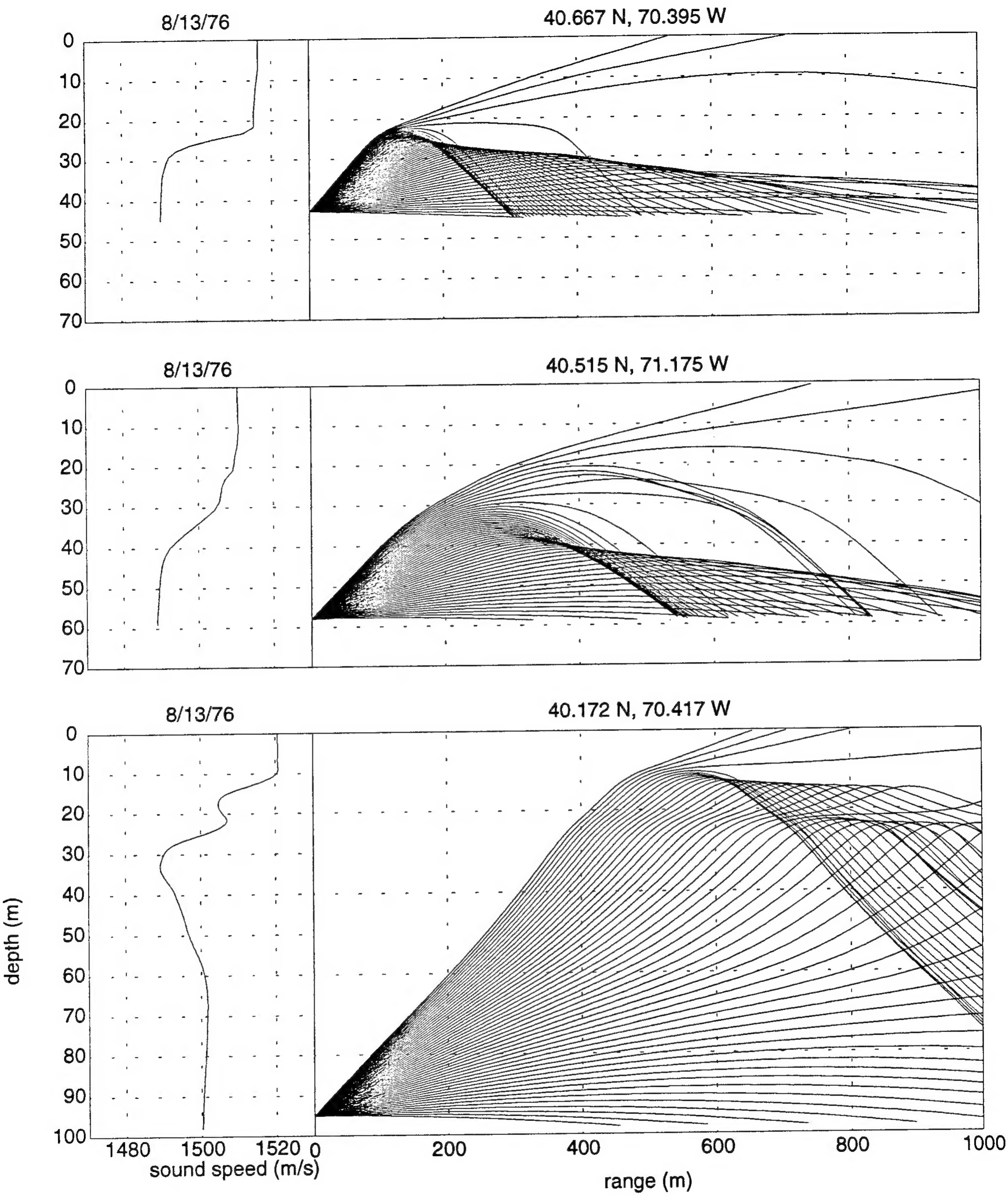


Figure 2. Raytrace diagrams for three profiles from the SAS region at sites having different bottom depths: <60 m (top), 68 m (middle), and >80 m (bottom).

FEATURES OF CASTS FROM 60–80 m BOTTOM DEPTH

Three profiles are shown in Figure 3 from the region along the north shipping lane (see Figure 1). The three raytraces display the features described earlier, with the caustic curve nearest the transmitter meeting the bottom at ranges of 400–550 m. To examine the timing resolution, we considered the travel times associated with these profiles at ranges after this first caustic. (At ranges before the first caustic, there is a single arrival.)

We need to assess, for a given transmitter/receiver range separation, if multiple arrivals can be separated in time. For the purpose of estimation, we will assume a signal bandwidth of 5 kHz, implying that rays arriving at the receiver more than 0.2 ms apart should be separable.

The profile from 61-m depth shown in the top panel of Figure 3 is from very near the proposed site. The ray diagram exhibits the complications that arise in this highly variable environment. The sound speed profile shows multiple gradients in the thermocline region and a weakly increasing gradient at depth that produces upward-bending rays near the bottom. Each change in gradient produces a new caustic. Consider a receiver just past the first caustic at a range of 425 m and a depth of 51 m (the depth of the transmitter). The nearly horizontal ray will arrive first, followed by a ray that turns above 30 m. The third ray, which arrives last, is the one we are interested in for a receiver at this range because it has a turning depth below 30-m depth. There is a difference of 0.138 ms between the first and second arrivals and 0.257 ms between the second and third. Note that the ray turning above 30 m has a lower amplitude. It will cause problems in measuring the near-horizontal ray if fluctuations increase its amplitude.

The other two profiles produce somewhat cleaner ray diagrams. For the profile in the middle panel of Figure 3, the travel time differences for the three rays arriving at 600-m range are 0.31 ms between the first and middle arrivals and 0.2 ms between the middle and last. The profile in the bottom panel of Figure 3 is especially good because of the narrow depth range of the high-gradient region near 20 m and the large depth range of decreasing sound speed below. For this profile, the arrival-time differences between the three rays are 2.96 ms and 0.51 ms for a receiver at a range of 600 m. So, except for the earliest pair in the top panel, the volume-propagating rays in Figure 3 are separable at ranges just past the first caustic.

We close this section with three additional points. First, most profiles we have examined have at least two caustics. For the profile in the bottom panel of Figure 3, we plot the ray arrival time vs depth at a range of 525 m in Figure 4. For depths below 25 m, three rays arrive. This arrival structure is quite robust and is a general property of the region between the two caustics. For a bandwidth of 5 kHz, rays in the shaded regions could not be separated.

Second, we have estimated the argument of the Airy function to be –1.5, where the Airy solution and the classical solution diverge near the caustic. The region where the Airy solution must be used on the "allowed" side of the caustic is equivalent to $f\Delta T < 0.39$, where f is the acoustic frequency and ΔT is the travel time difference for the rays that form the caustic. By doubling this size, we can include the "forbidden" as well as the "allowed" side of the caustic. In the region of the first caustic curve, the horizontal size is about

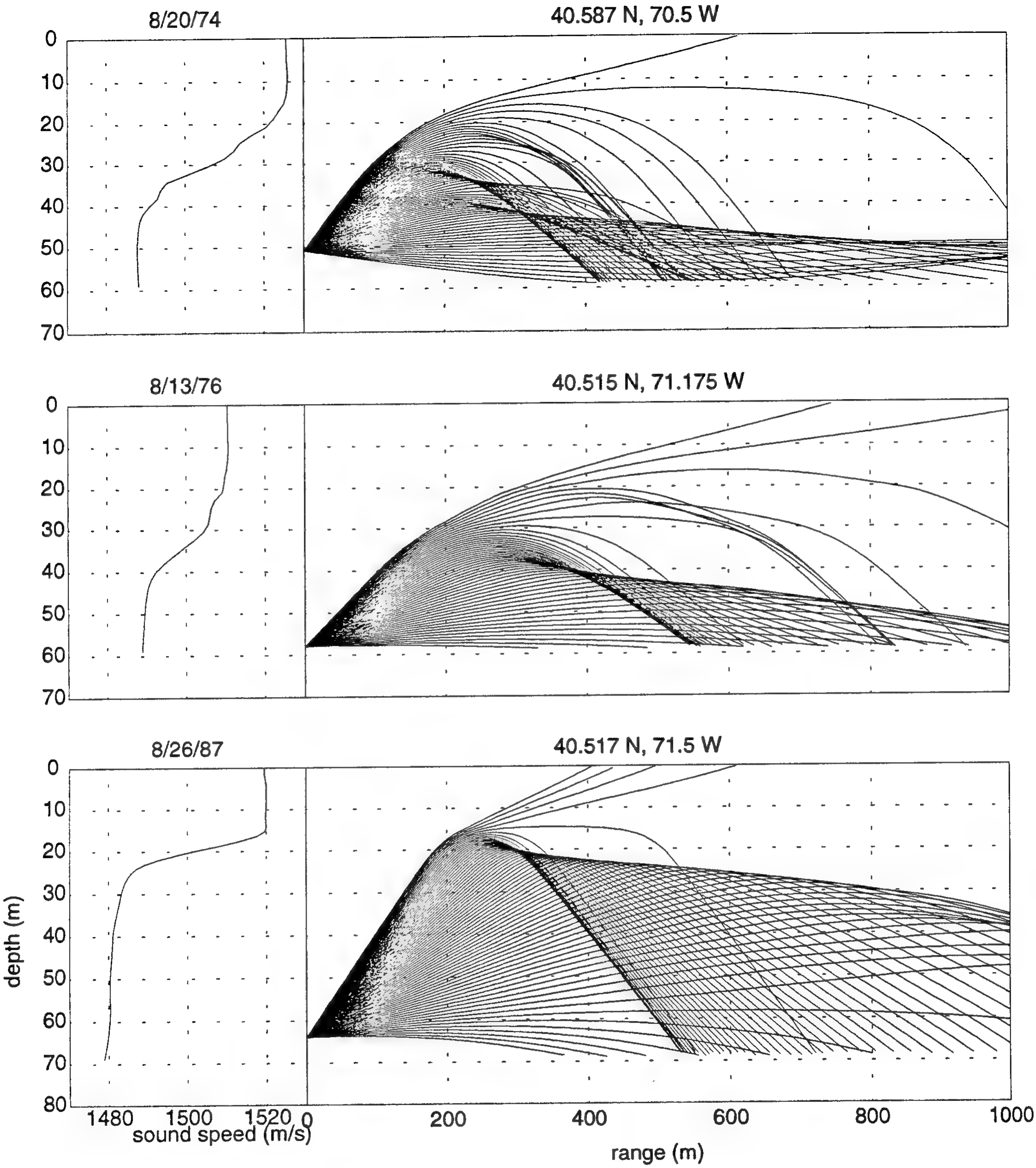


Figure 3. Raytrace diagrams from three example profiles made where the bottom depth was 60-80 m. Top: bottom depth 61 m, source depth 51 m. Middle: bottom depth 71 m, source depth, 58 m. Bottom: bottom depth 74 m, source depth 64 m.

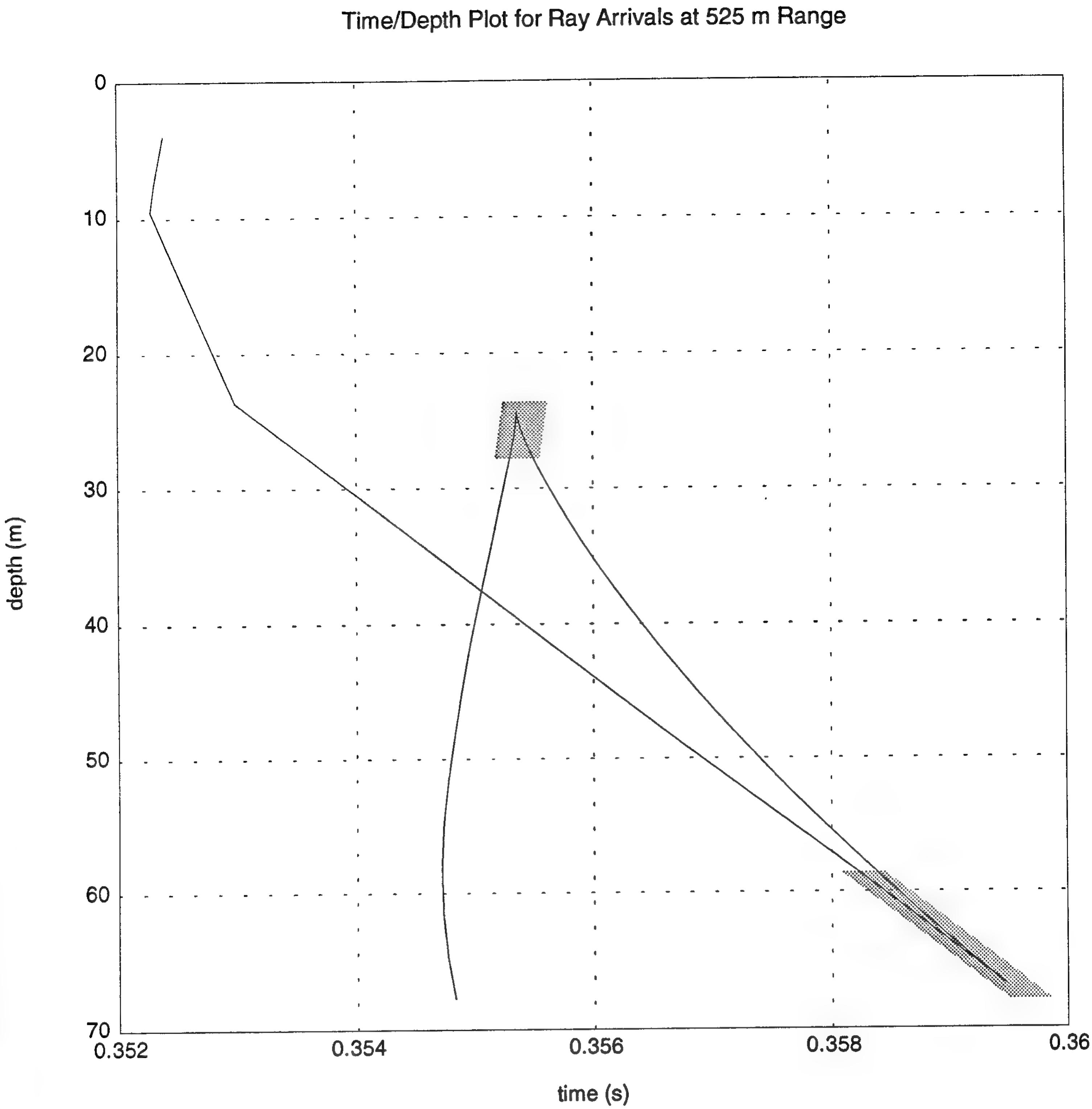


Figure 4. Time/depth plot for the rays shown in the bottom panel of Figure 3. The shaded areas are arrivals that are separated by less than 0.2 ms. A pulse with a bandwidth less than 5 kHz could not be used to separate arrivals in the shaded regions.

30 m for an acoustic frequency of 20 kHz. For higher frequency transmissions, this region will be narrower. Outside this region, the classical solution is adequate.

Third, for simplicity we have discussed only volume propagation. Clearly, bottom and surface reflections will be present. An example raytrace using the profile from the bottom panel of Figure 3 is shown in Figure 5. For a receiver at 600-m range, the first five ray arrivals occur at 405.45 ms, 405.92 ms, 408.41 ms, 408.92 ms, and 411.47 ms. The first, third, and fourth are volume rays; the second and last are bottom reflected. Thus for this profile and range, separation of all rays is possible. For the shallower case (depth <60 m), the reflected arrivals will be more of a problem than at depths of 60–80 m because the entire arrival pattern will be compressed in time. For deeper scenarios, an increasing sound speed near the bottom is more likely and will cause similar timing problems with reflected rays. Note that even in situations where bottom bounce is a problem, interpretation of the signal would still be possible if the acoustic scintillations are weak.

A POSSIBLE STRATEGY

The purpose of the SAS experiment is to determine the effect of random sound speed fluctuations on the horizontal scales of the acoustic phase and amplitude. Because shallow-water environments commonly involve two layers, measuring both the near-horizontal rays and the rays that turn in the thermocline is required. The strongest fluctuations will be in the thermocline whereas the nearly horizontal rays will traverse weaker fluctuations. Because of the limitation in separating rays in time, it is likely that both types of rays can't be monitored simultaneously at the same range. This implies a scenario where the equipment is placed on the bottom at one range for one set of measurements and then moved to a second or even a third range to sample different sets of rays. At a range before the first caustic, the nearly horizontal rays would be monitored, and the range could be selected so that the rays reflecting from the boundaries could be time-gated out of the record. At a range past the first caustic, the higher-angle rays that sample the region of the thermocline arrive later than the near-horizontal ray. It is likely that the near horizontal ray would be contaminated by a bottom return. At this longer range, the near-horizontal and bottom-reflected rays would be ignored, and the thermocline-turning rays would be monitored. The receivers would have to be sufficiently past the caustic so that the two rays from the thermocline could be separated. Finally, positioning the array in the Airy region may also be desirable.

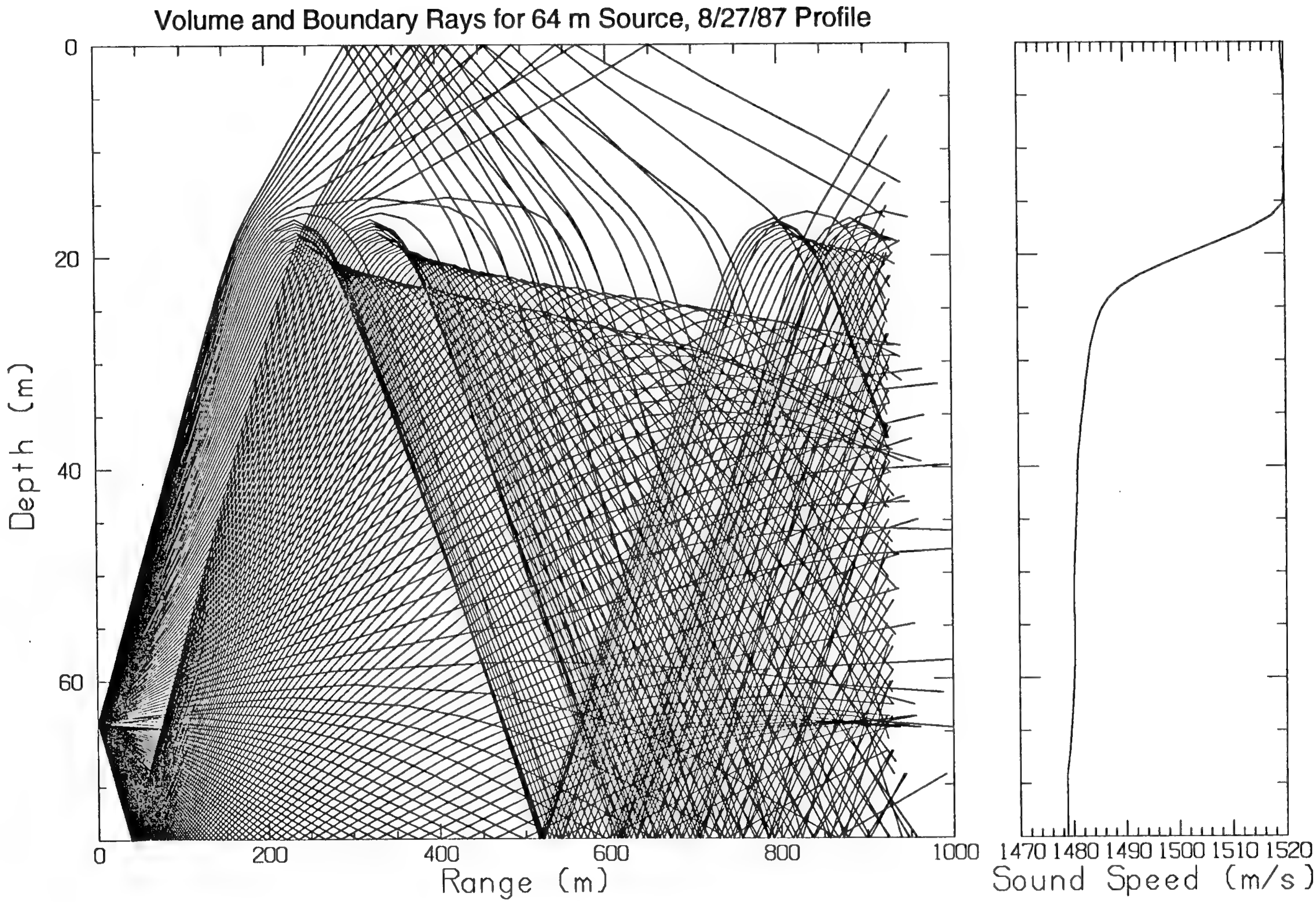


Figure 5. Raytrace using the profile from the bottom panel of Figure 3 that includes surface and bottom reflections.

CONCLUSION

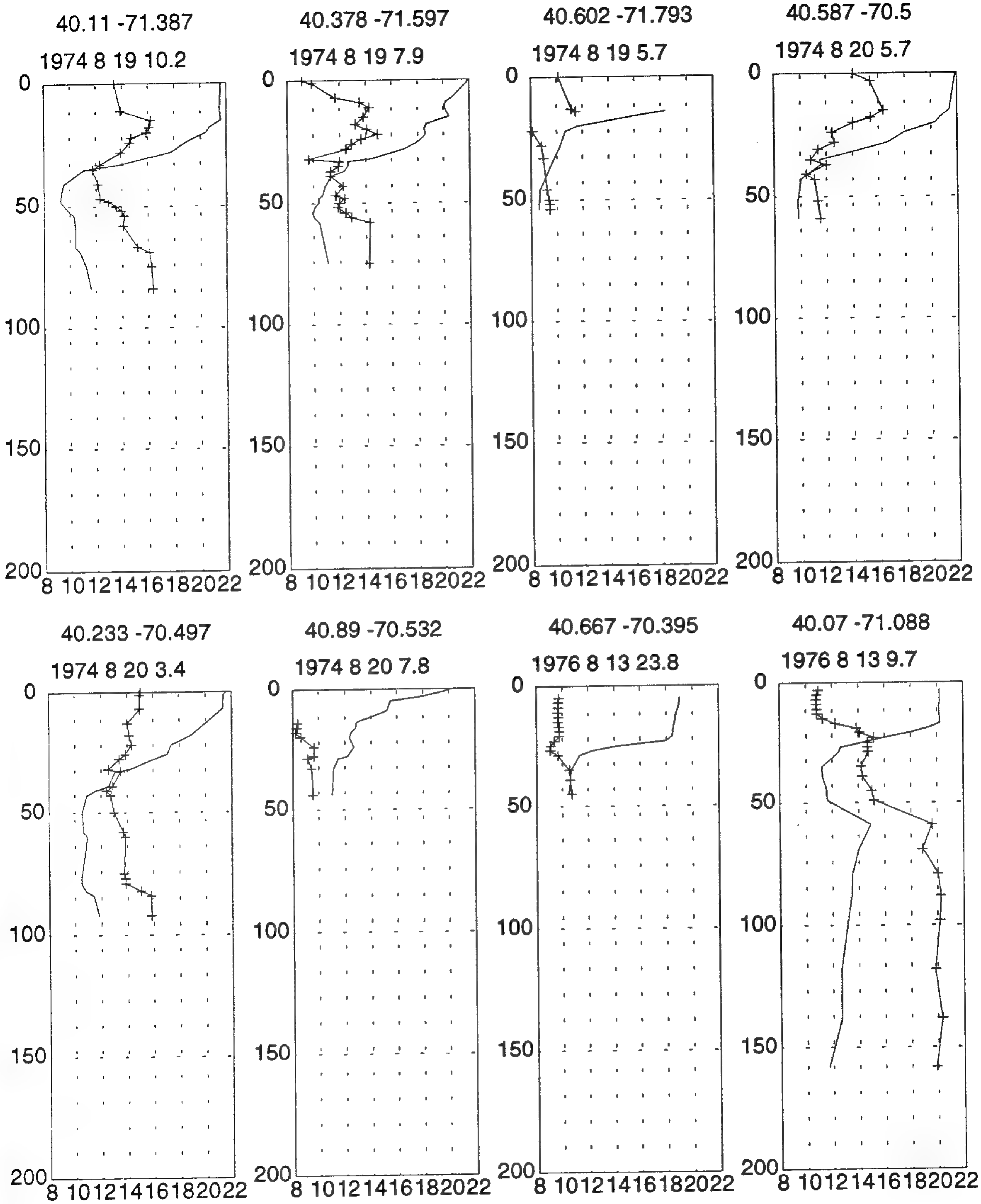
We have examined historical sound speed profiles taken in July and August near the SAS site and identified general characteristics of the propagation regime. We make the following points:

- Sound speed profiles from the SAS region exhibit two layers, with a high-speed surface layer that is 10–20 m thick overlying lower-speed water.
- Because of the high-gradient region below the surface layer, rays from a transmitter placed 10 m above the bottom form two caustics at increasing range. At ranges before the first caustic, a single, near-horizontal ray would be received (ignoring rays that have interacted with the boundaries). At ranges between the two caustics, three rays would be received. The near-horizontal ray would arrive first followed by two rays that sample the high-gradient part of the profile.
- We need to measure energy traversing both the near-horizontal and the shallow paths. To do so may require moving to different ranges during the experiment.
- We found favorable propagation characteristics in profiles from sites having bottom depths of 60–80 m. The proposed SAS site at 40.5°N, 70.5°W is workable; it has a bottom depth of 70 m.
- For depths >80 m, it is likely that propagation paths with the strongest fluctuations will not be sampled by a receiving tower within 1000-m range. We believe sampling these paths to be an essential part of the experiment.
- South of 40.5°N, the influence of open-ocean water from off the shelf is related to bottom depth and distance from the 100-m isobath. The off-shelf water causes ducting and upward-refracting rays near the bottom. Acoustic energy reflecting from the bottom will be more of a problem in this case.
- Ray traces for sites having bottom depths less than 60 m show significantly less range before the first caustic is reached. Therefore, fluctuations will not have much chance to build up. The region between the two caustics is also shortened. Separating multiple arrivals (including bottom and surface reflections) will be more difficult for these sites.

We have included as an appendix the 30 temperature/salinity casts found in the archive. Raytraces made using profiles not used in Figure 2 or 3 are also shown. These have a coarser angle separation.

APPENDIX

TEMPERATURE/SALINITY CASTS
AND
RAYTRACES



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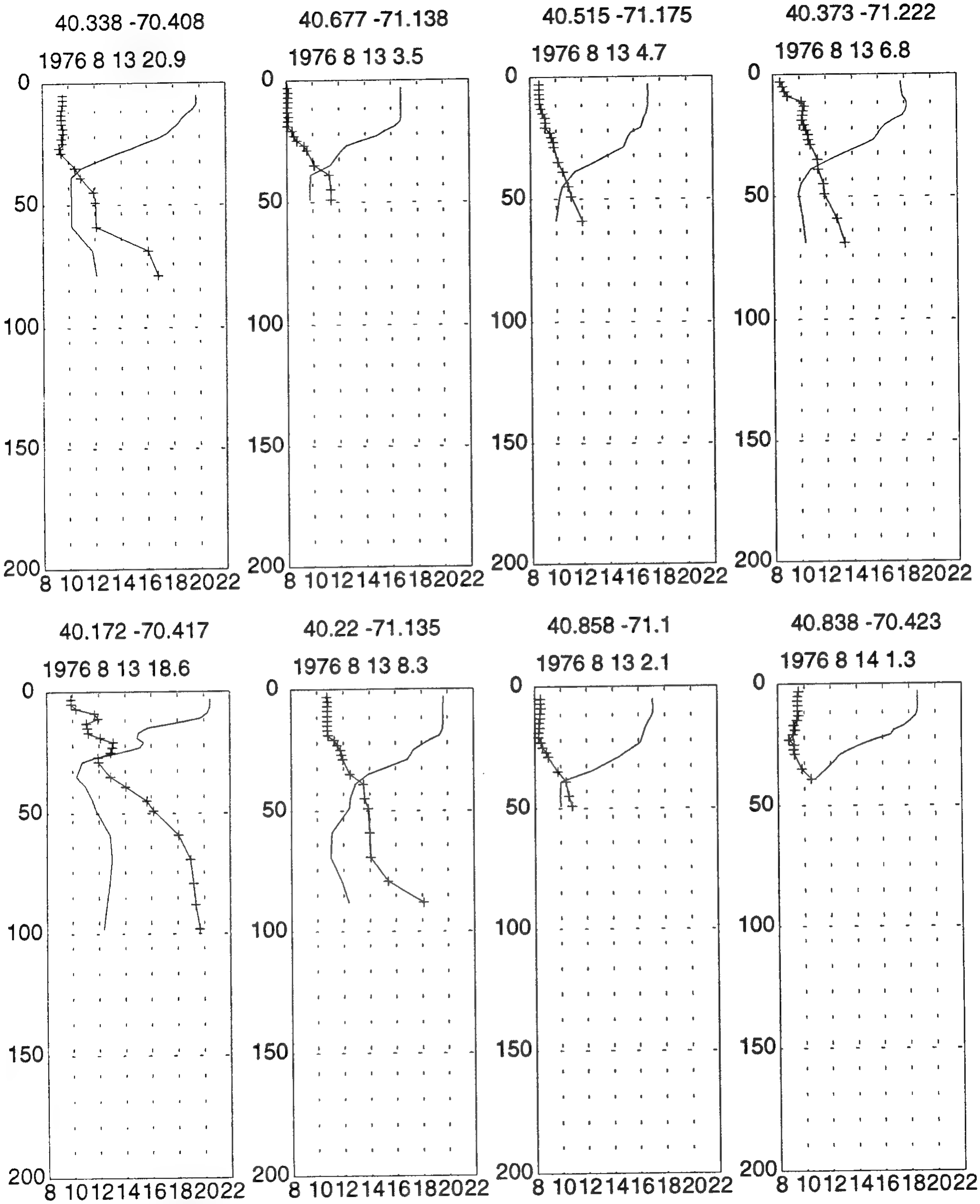
(solid line = temperature)



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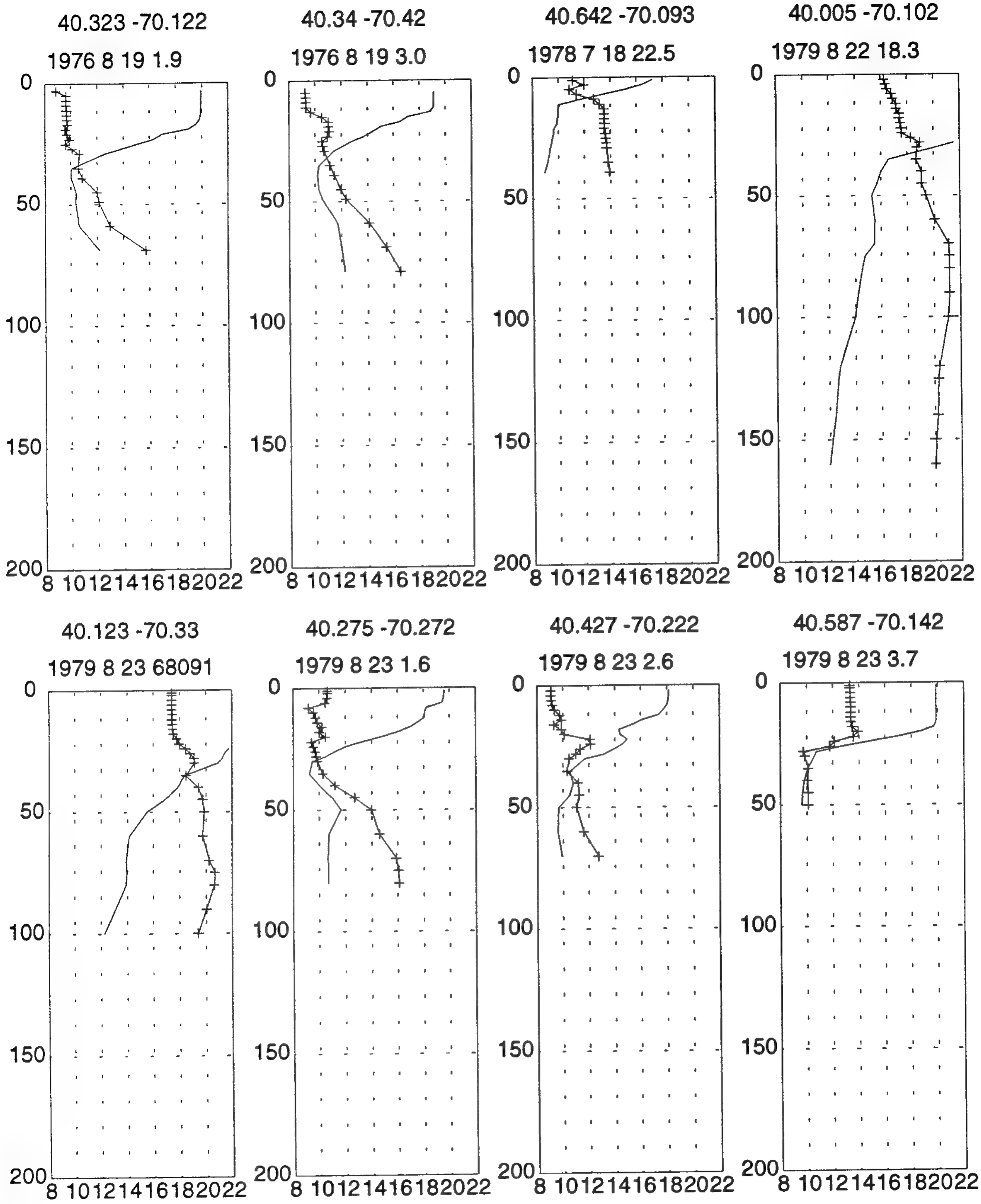
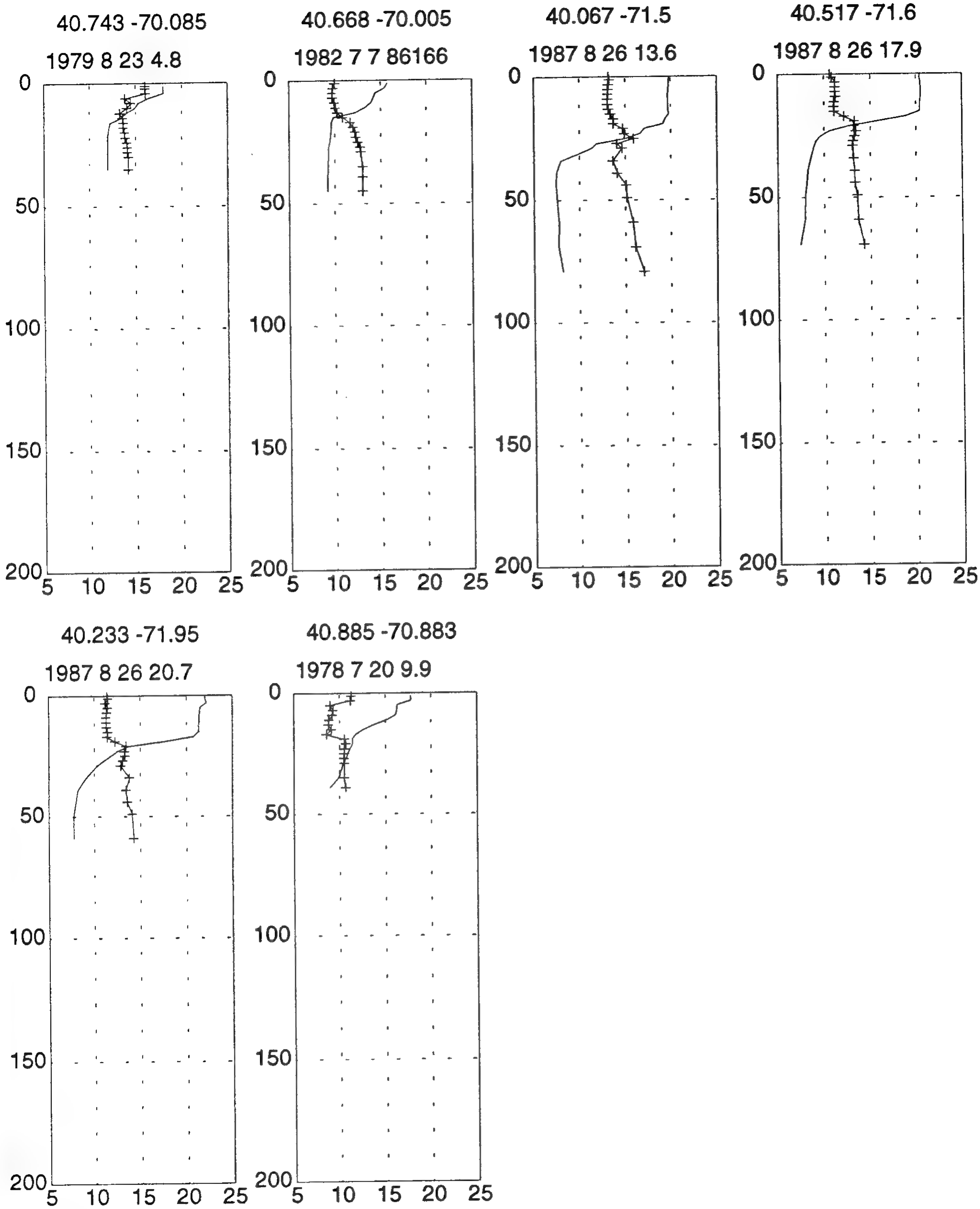
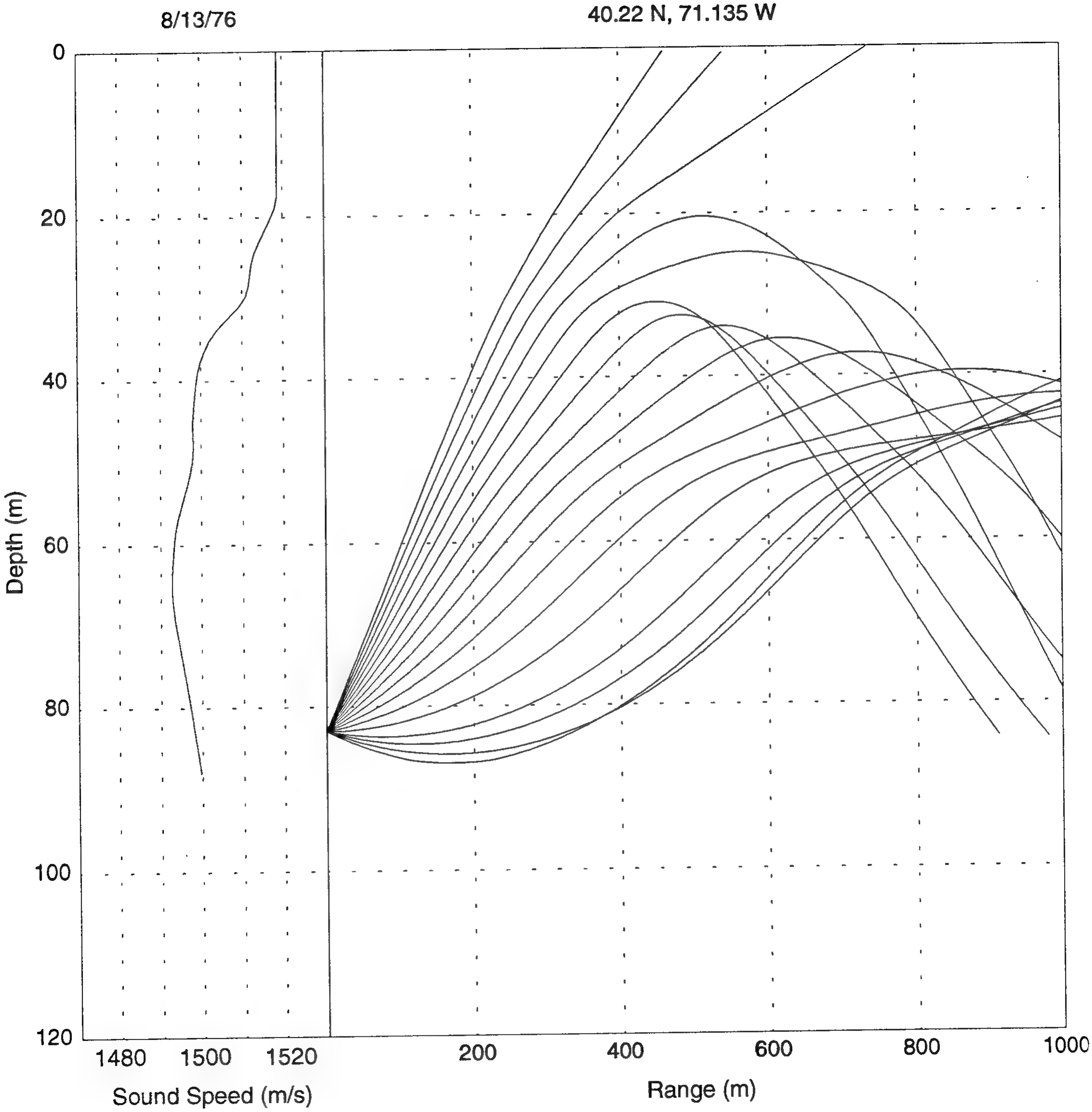


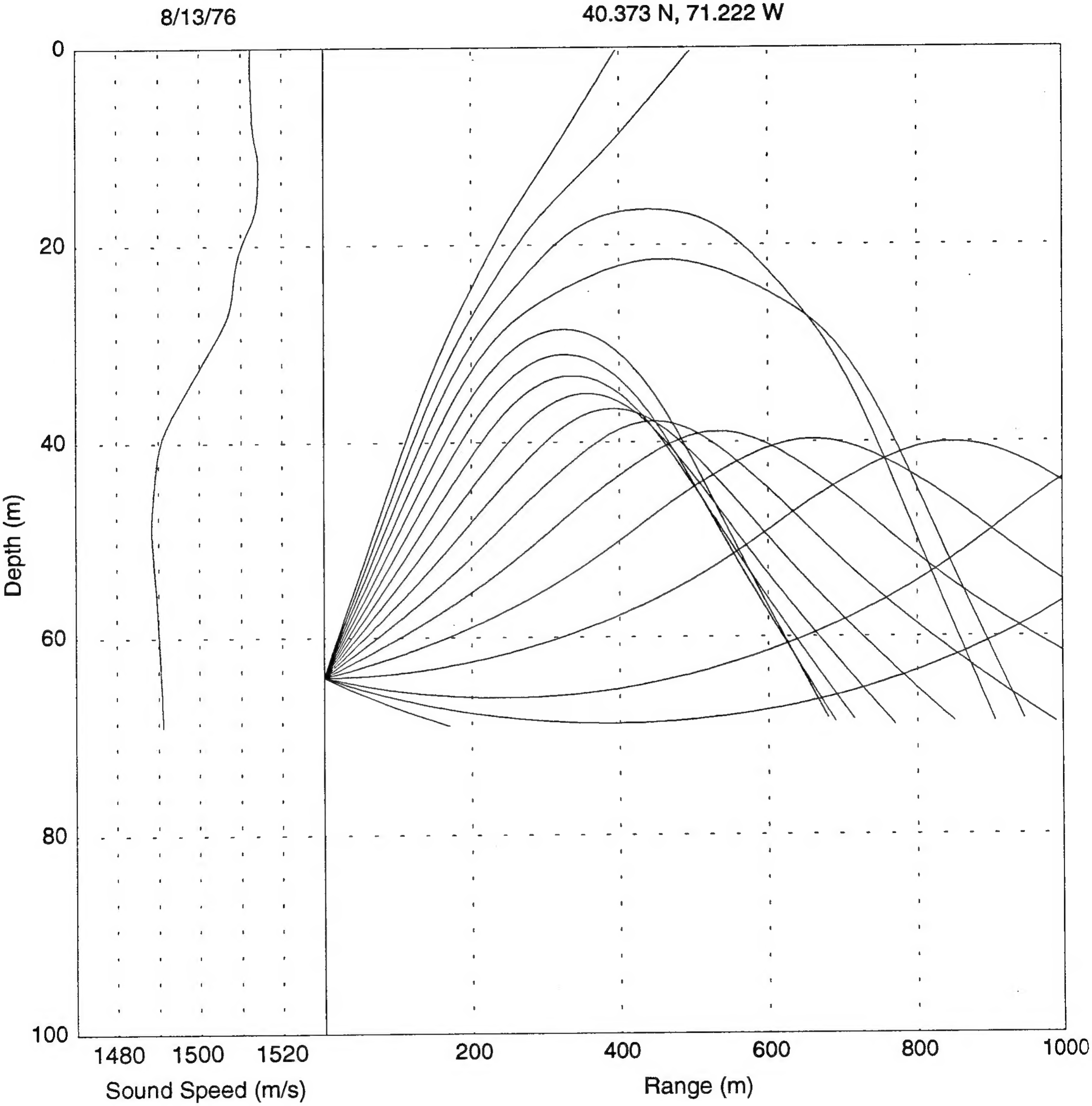
Salinity range= [32.5 - 36]
except for 3rd graph= [31 - 34.5]



Salinity range= [31 - 35]



8/13/76
40.22 N, 71.135 W
0
20
40
60
80
100
120
Depth (m)
1480
1500
1520
Sound Speed (m/s)
200
400
600
800
1000
Range (m)



8/13/76
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100
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Sound Speed (m/s)
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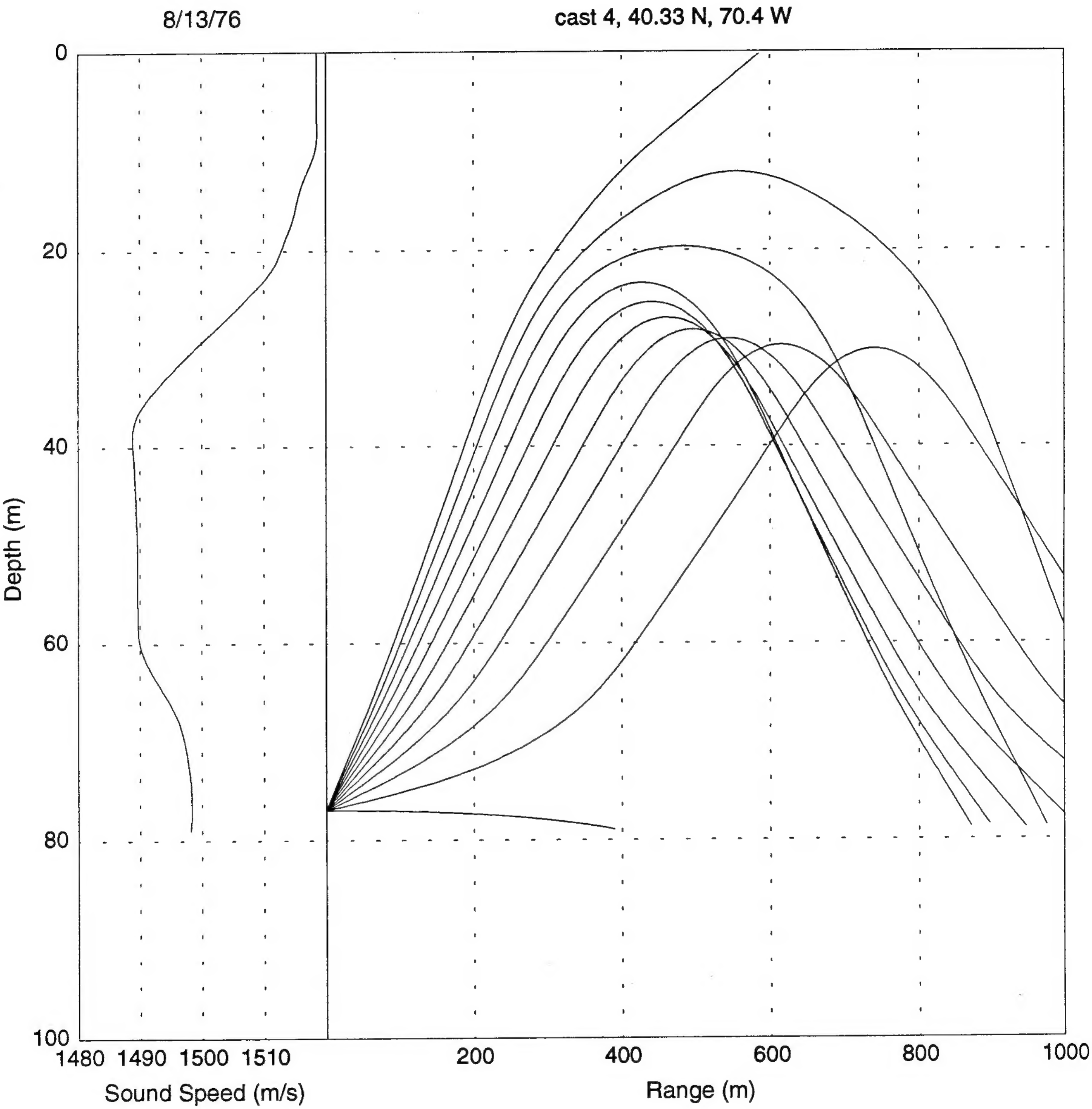
600
800
1000
Range (m)


8/13/76
cast 4, 40.33 N, 70.4 W
Depth (m)
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60
80
100
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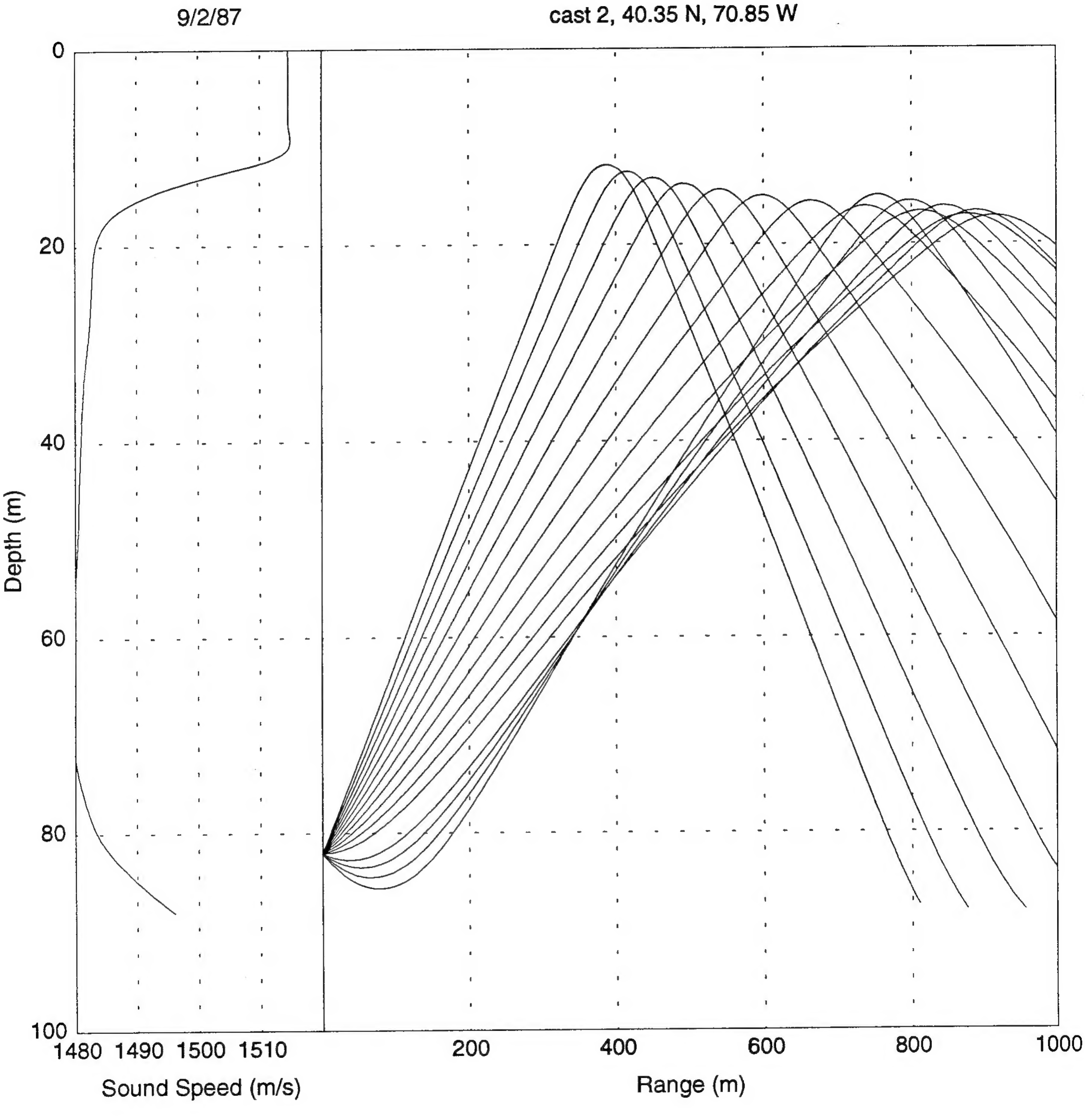
400
600
800
1000
Range (m)



9/2/87
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20
40
60
80
100
Depth (m)
1480 1490 1500 1510
Sound Speed (m/s)
200
400
600
800
1000
Range (m)

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